LA-UR-14-21482

Approved for public release; distribution is unlimited.

Title: Design Optimization of Structural Health Monitoring Systems

Author(s): Flynn, Eric B.

Intended for: LANL Engineering Capabilities Review

Issued: 2014-03-06

Design Optimization of Structural Health Monitoring Systems

Eric B. Flynn, PhD

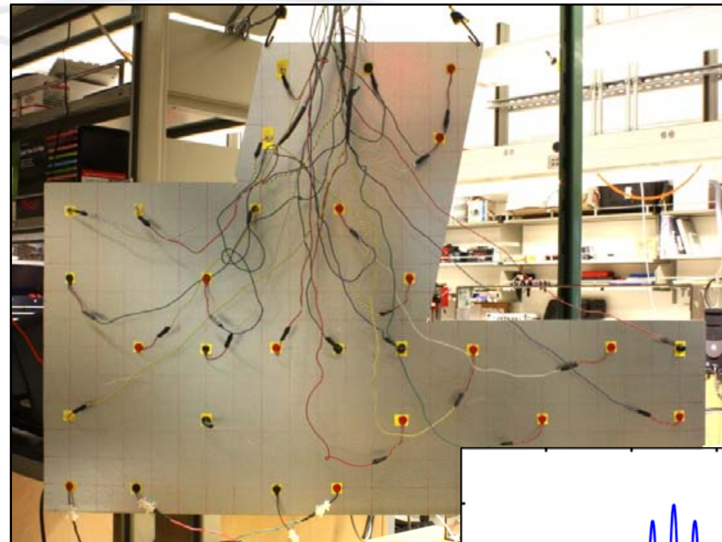
Abstract

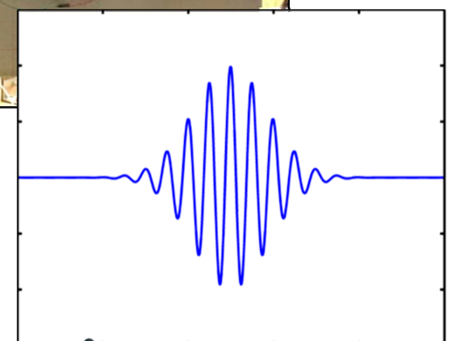
Sensor networks drive decisions. Approach: Design networks to minimize the expected total cost (in a statistical sense, i.e. Bayes Risk) associated with making wrong decisions and with installing, maintaining and running the sensor network itself. Search for optimal solutions using Monte-Carlo-Sampling-Adapted Genetic Algorithm. Applications include structural health monitoring and surveilance.

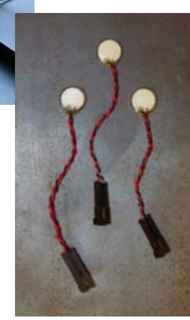
System Design

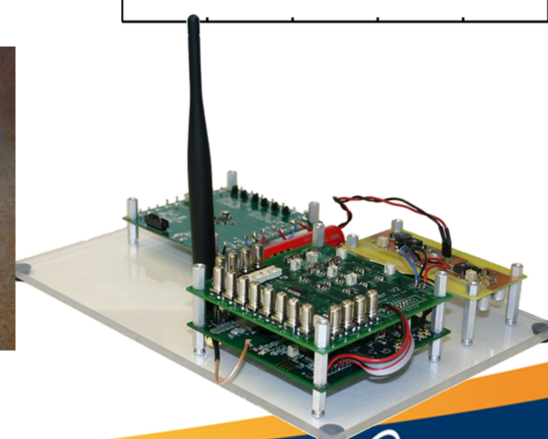
Example design choices

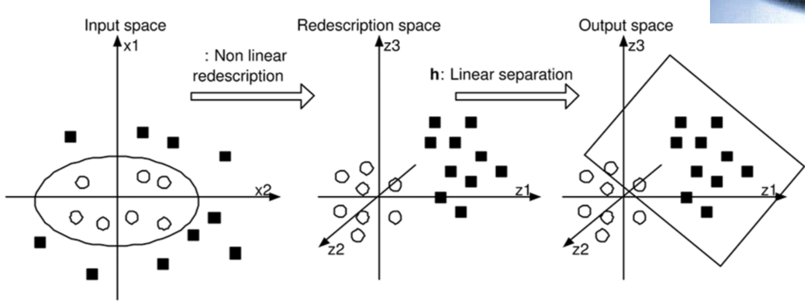
- Detection Algorithm/Classifier
- Sensor Count
- Sensor Placement
- Sensor Orientation
- Sensor Type
- Interrogation Signal
- Duty Cycle





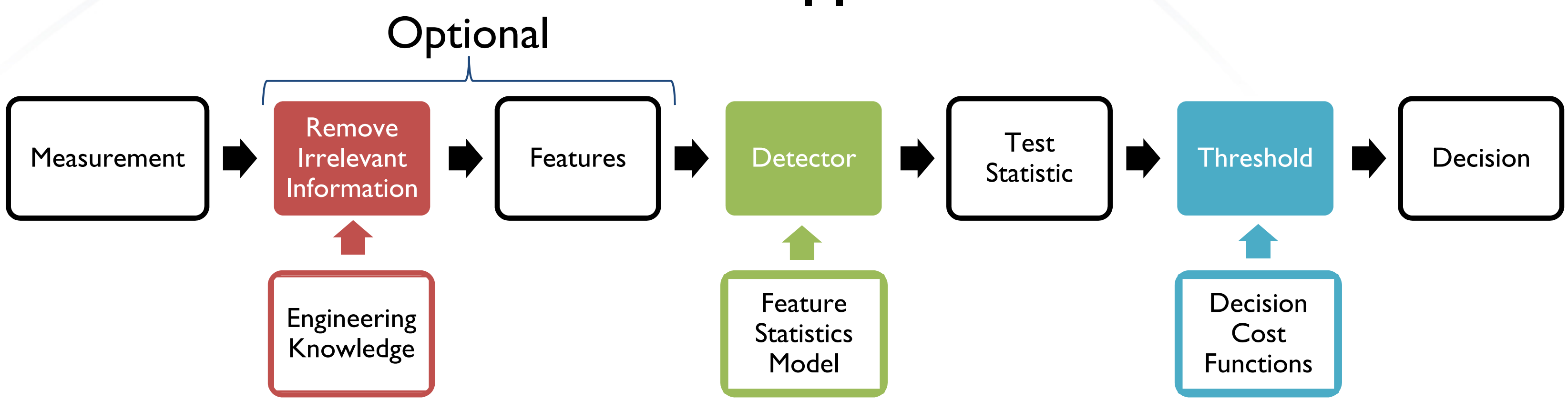




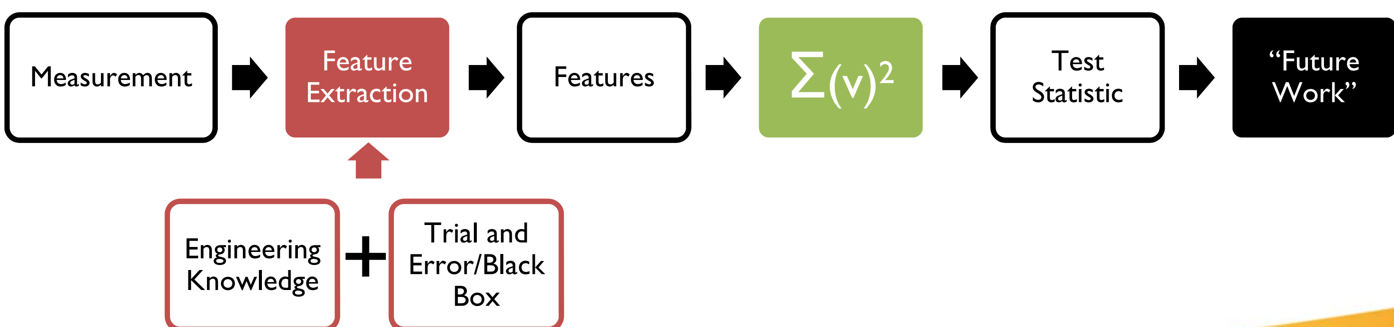


Structural Health Monitoring

LANL Approach



What everyone else does…



Suggested Metric: Bayes Risk

Decision Cost Function

Particular System Design

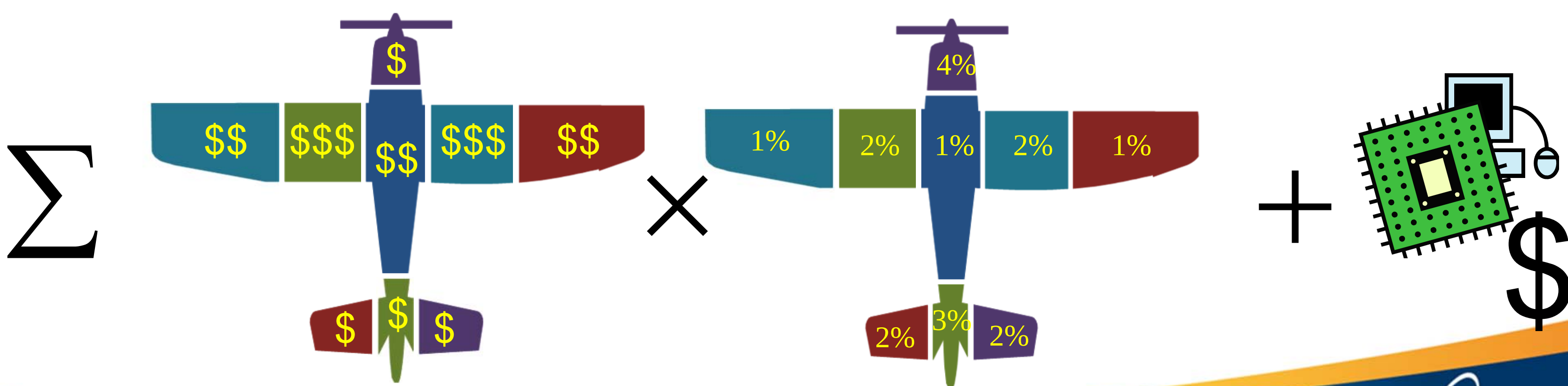
$$E(L) = \sum_{\theta,\hat{\theta}} \mathrm{L_d}\left(\hat{\theta},\theta\right) \mathrm{P}\left(\hat{\theta} \middle| \theta, e\right) \mathrm{P}(\theta) + \mathrm{L_e}(e)$$

Expected Loss
(Bayes Risk)

True State

Hardware Cost of
the Design

Decision State



Defining the Problem

- What are the **relevant physical states** and their **probability** of becoming a reality?
- What **actions** is the system intended to direct in response to the physical states?
- What are the **decision costs** of taking each of those response actions?
- What are the **system hardware costs** associated with the surveillance design?

$$\mathrm{E}(L) = \sum_{\theta,\hat{\theta}} \mathrm{L_d}\left(\hat{\theta},\theta\right)\mathrm{P}\left(\hat{\theta}\middle|\theta, e\right)\mathrm{P}(\theta) + \mathrm{L_e}(e)$$

Two-part Design Process

Hardware Design

Physical State

Algorithm Design

$$e \longrightarrow \boldsymbol{v} \sim \boldsymbol{v}(\theta, e) \longrightarrow \hat{\theta} = \delta(\boldsymbol{v}, e)$$

Measurements/
Features

$$\mathrm{P}\left(\hat{\theta} \middle| \theta, e\right)$$

Performance Statistics

$$\mathrm{E}(L) = \sum_{\theta,\hat{\theta}} \mathrm{L_d}\left(\hat{\theta}, \theta\right) \mathrm{P}\left(\hat{\theta} \middle| \theta, e\right) \mathrm{P}(\theta) + \mathrm{L_e}(e)$$

Detection Algorithm Design

The Bayes optimal detection algorithm:

Make the decision that minimizes expected risk given measurements/features.

Optimal Decision

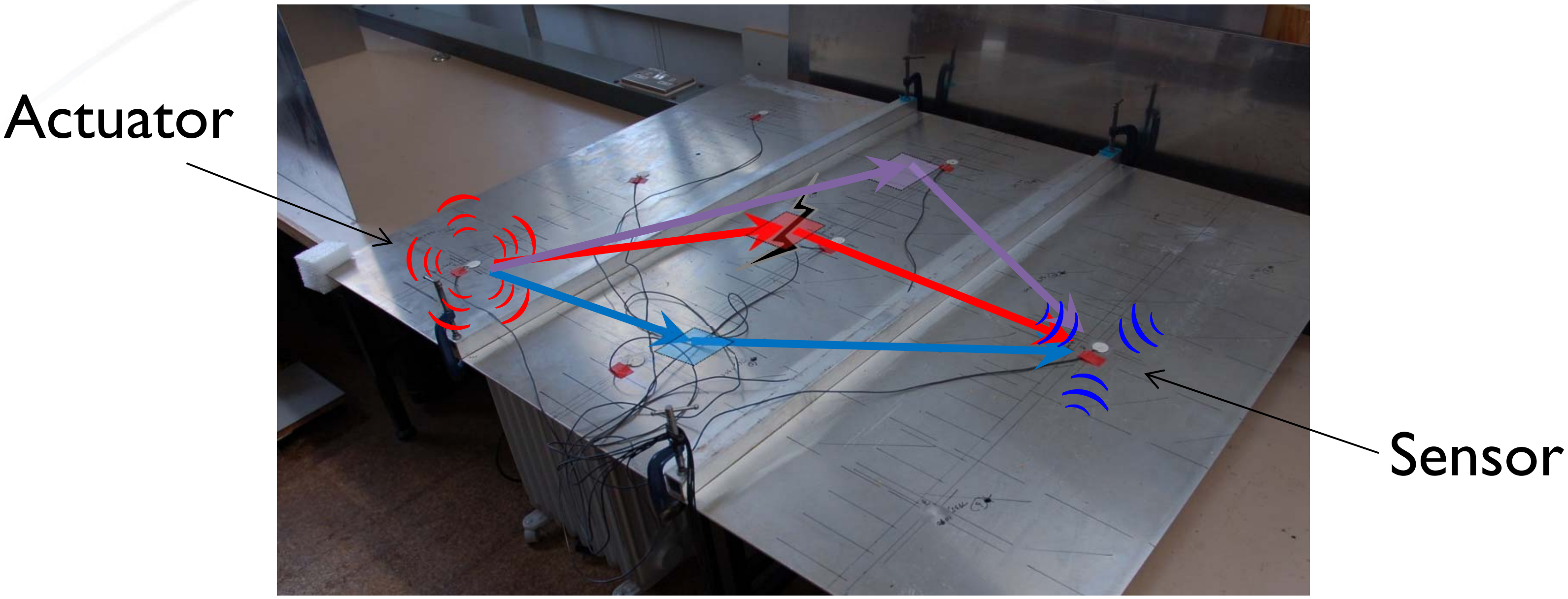
Likelihood Function (Feature Statistics)

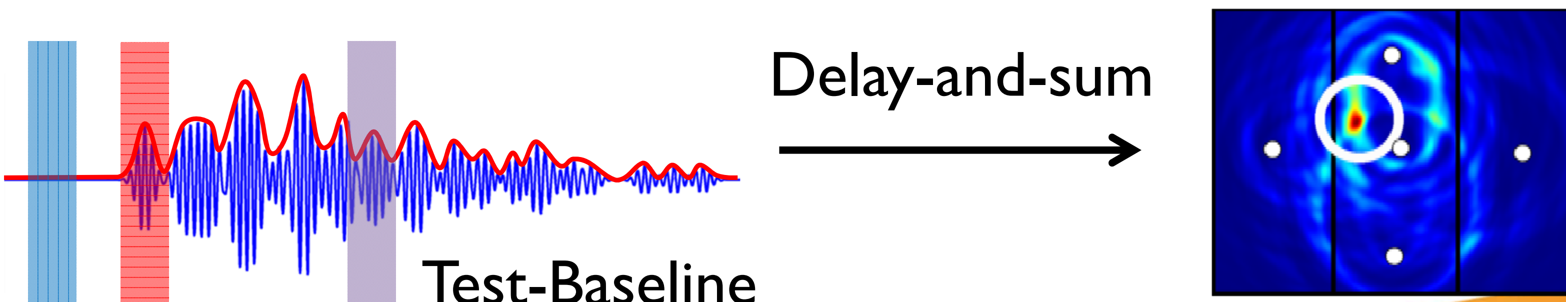
Decision Cost Function

$$\hat{\theta}^* = \delta^*(\mathbf{v}, e) = \arg\min_{\hat{\theta}} \sum_{\theta} \mathrm{p}(\mathbf{v}|\theta, e)\, \mathrm{L}_{\mathrm{d}}(\hat{\theta}, \theta)\, \mathrm{P}(\theta)$$

Sum over potential physical states

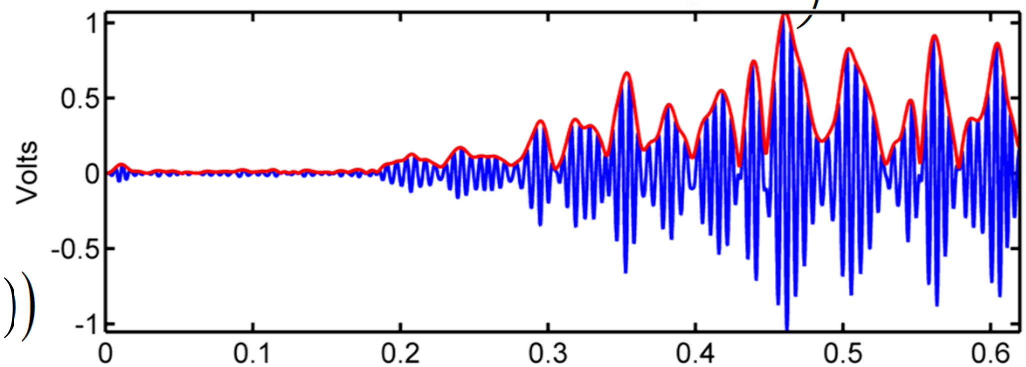
Embedded Ultrasonic Inspection





Maximum *a posteriori* probability estimate

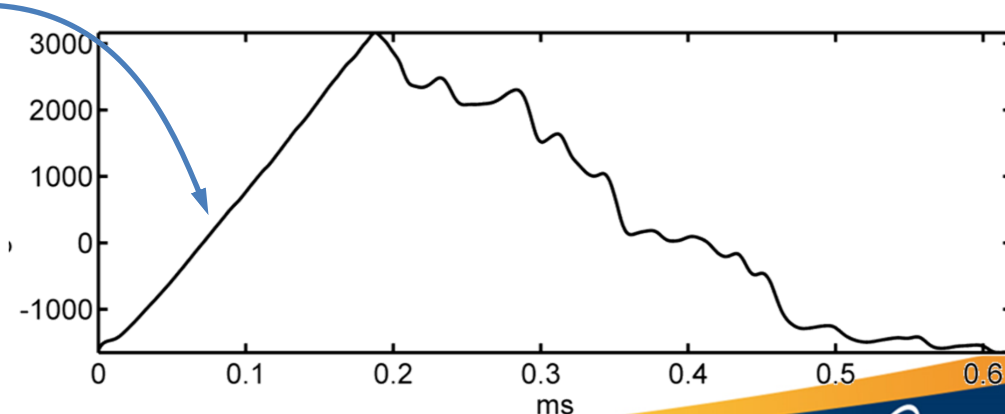
$$L\left(\theta_{xy}\right)=\sum_{\text{Pairs}}\left(\sum_{\text{Time Samples}}\log\left(p\left(v_1\left|\theta_{xy}\right.\right)\right)+\log\left(p\left(v_2\left|\theta_{xy}\right.\right)\right)\right)$$



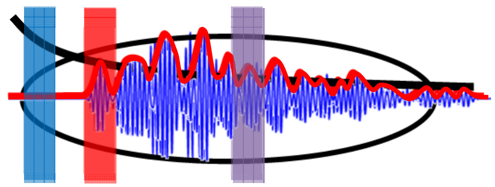
Time of Flight

$$L(\boldsymbol{x})=\sum_{m=1}^{M}w_m\left[\eta_m(\boldsymbol{x})\right]+\log\left(p(\boldsymbol{x})\right)$$

$$w_m[\eta]=-\eta\log\left(\sum_{n=1}^{\eta}v^2{}_m[n]\right)-(N-\eta)\log\left(\sum_{n=\eta+1}^{N}v^2{}_m[n]\right)+\log\left(\eta!(N-\eta)!\right)$$

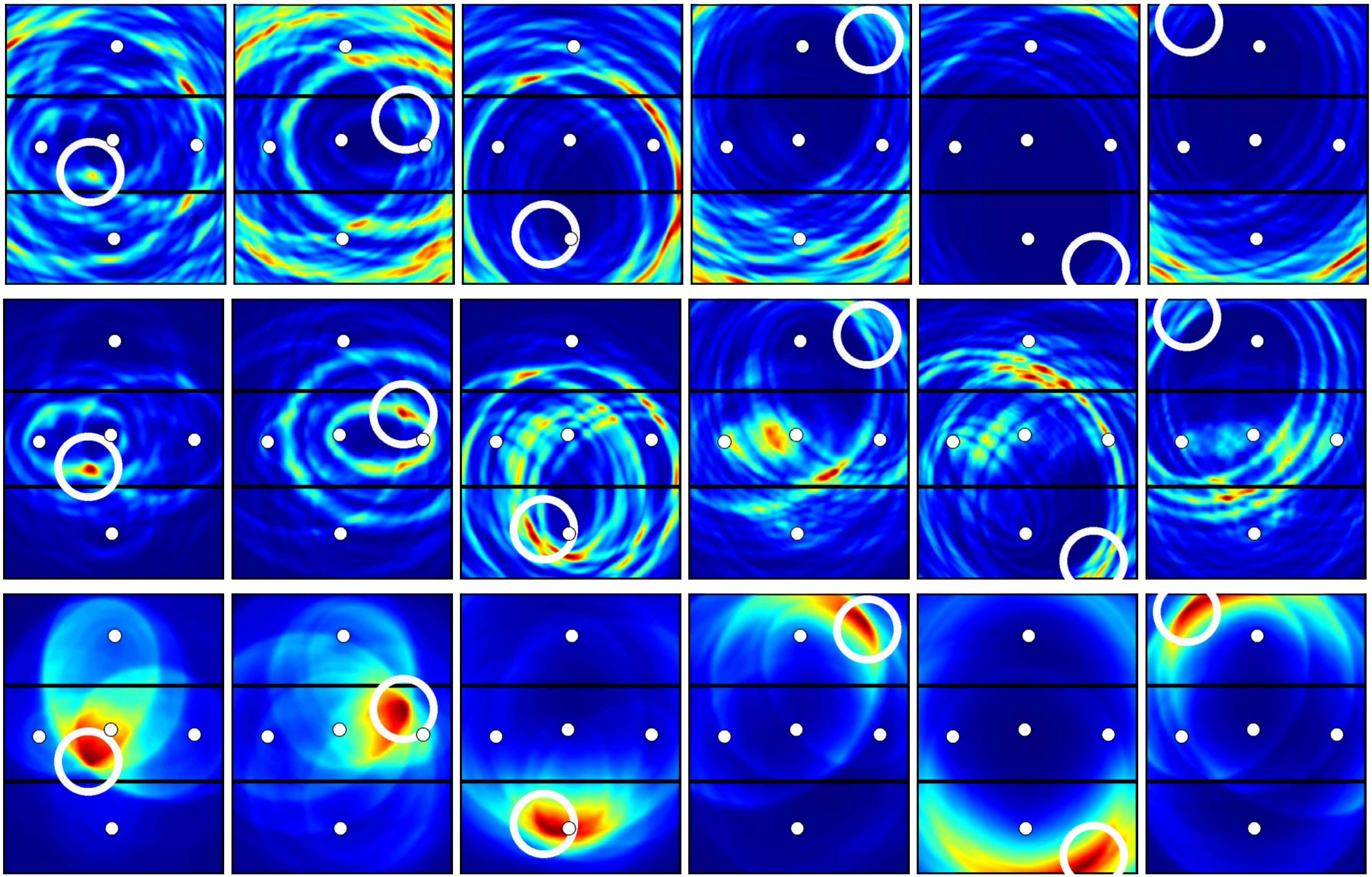


Comparison



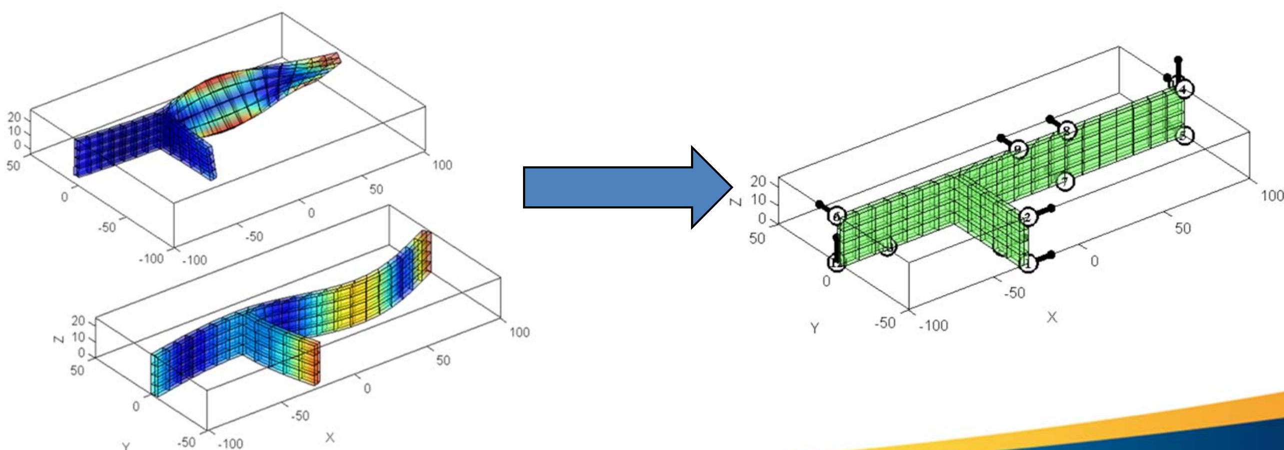
Envelope and Delay and Sum

Statistical Modeling
Delay and Sum



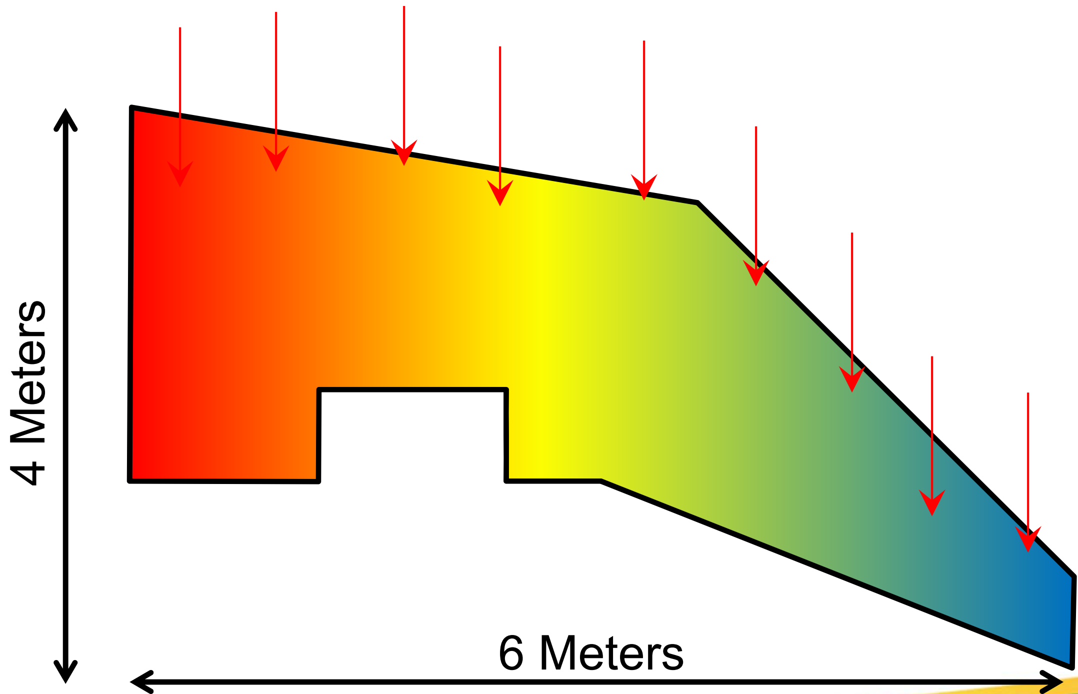
Hardware Design

- Define the monitoring problem
- Establish feature measurement process
- Design detection algorithm based on measurement statistics **parameterized to hardware design variables**
- Calculate system statistics and performance (Bayes Risk)
- Search hardware design space for optimum

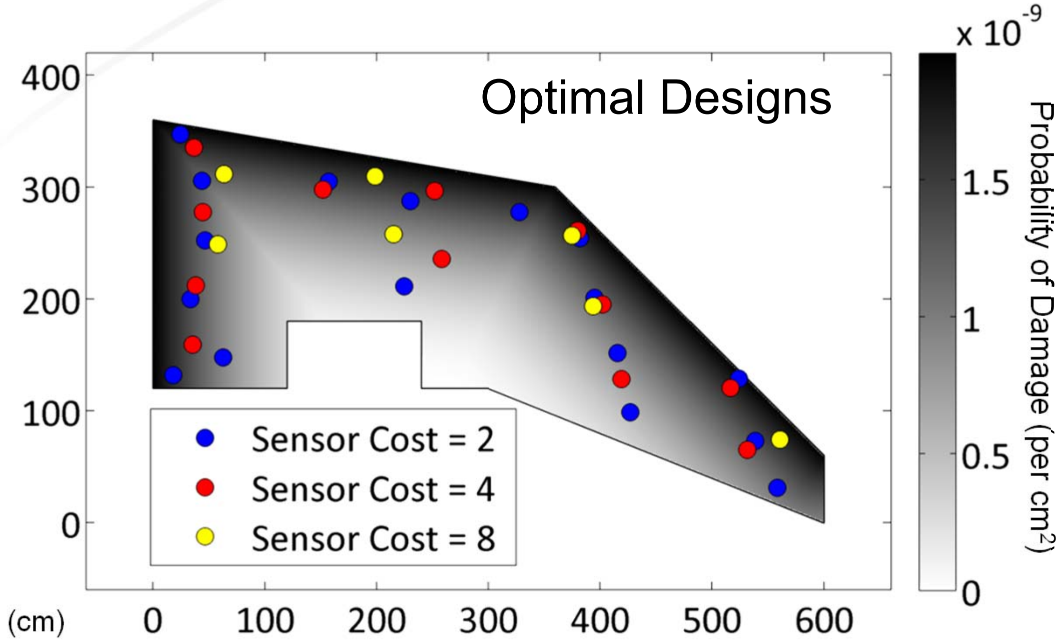


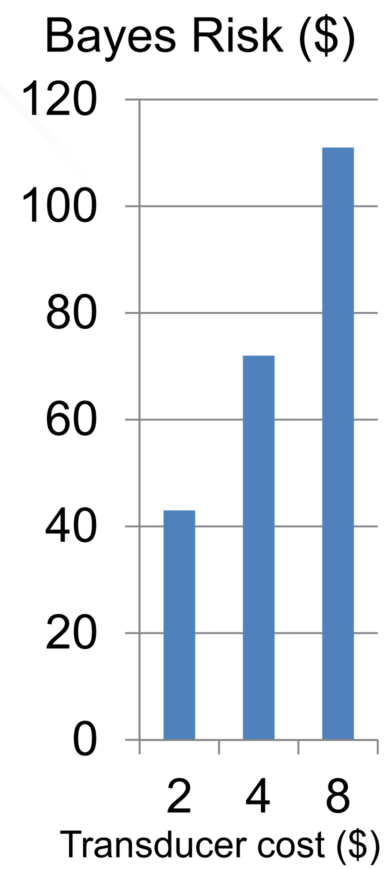
Hardware Design Example

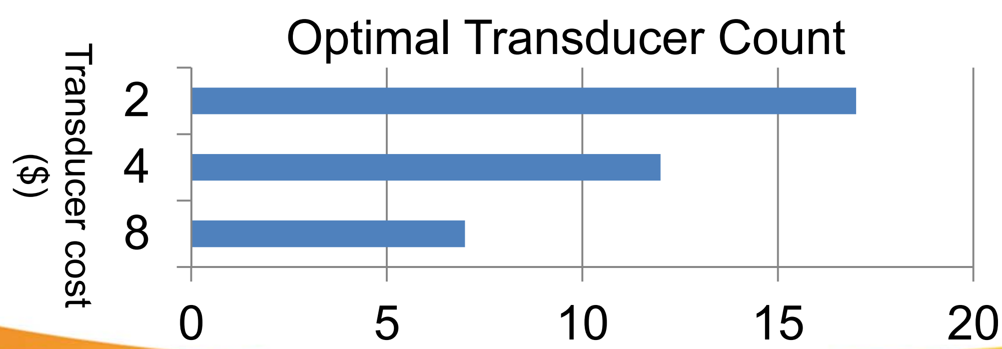
- Monitoring of aerospace component skin
- Structure undergoes bending and torsional fatigue loading and is subject impacts on its leading edges
- Optimize the number and the placement of transducers



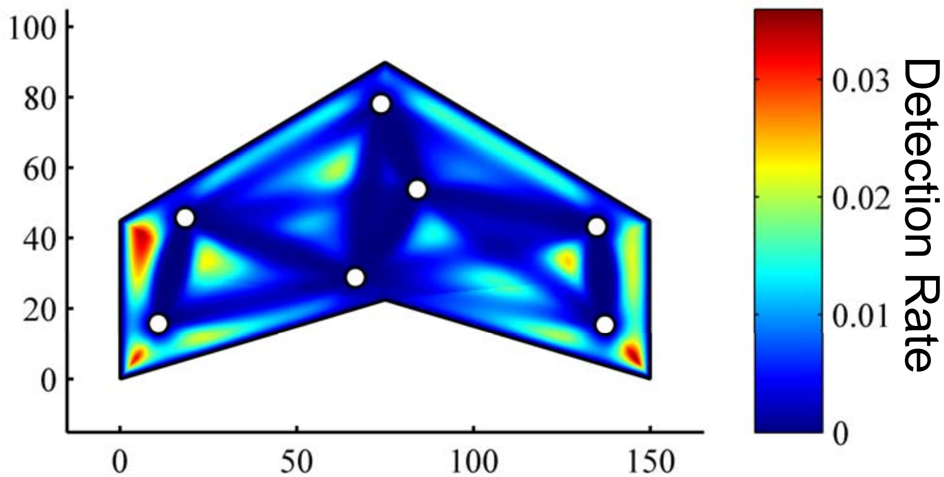
Optimization Results





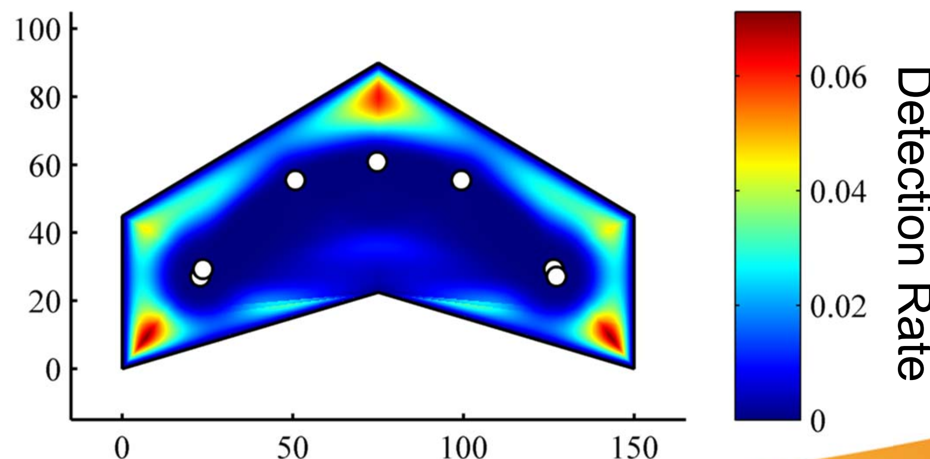


Sensor Failure



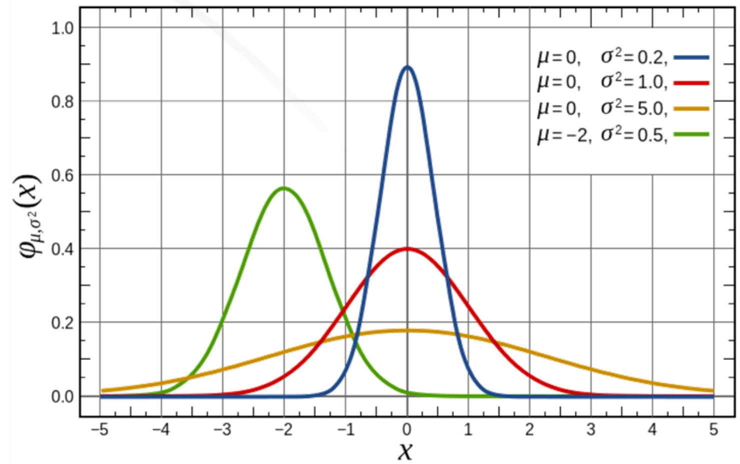
No Sensor Failure

10% Chance of Sensor Failure



The Hard Truth

The world doesn't look like this:



Which means:

- Optimal detectors are intractable
- Detector statistics are intractable
- Detector performance is intractable
- Sensor network performance is intractable

Brute Force

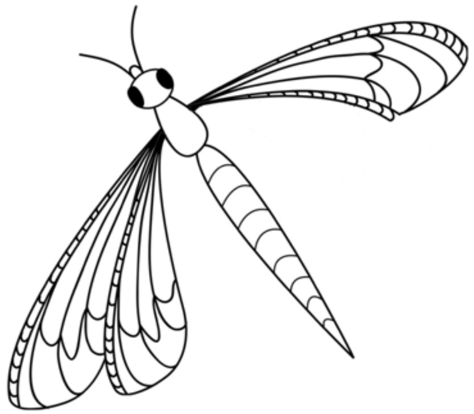
Monte Carlo your way to a performance estimate

- Generate random samples
- **Measure**
- **Detect / Score**
- Threshold
- Estimate the Bayes Risk

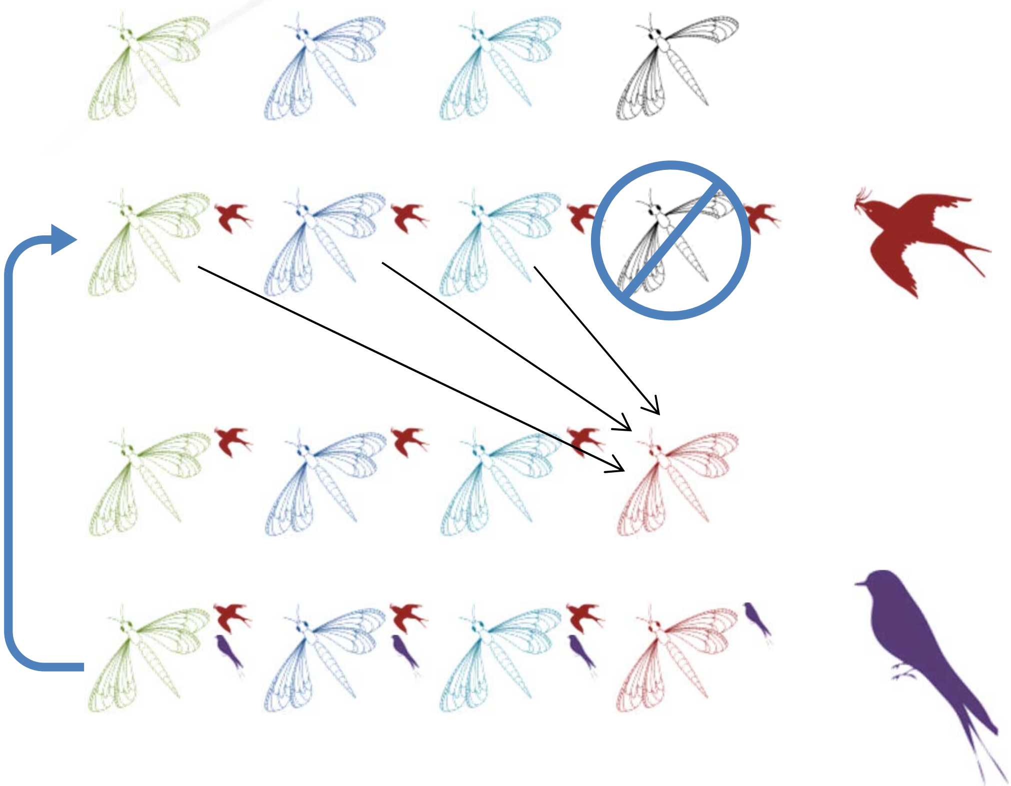
Problem: Takes a long time!

Solution: Sampling Adapted Search

- It doesn't take a "life-time" worth of Monte Carlo trials to determine that some designs just won't cut it



A Smarter Genetic Algorithm



Generate population

Generate small random sample, subject, and evaluate performance

Destroy the worst performers

Survivors remember past samples

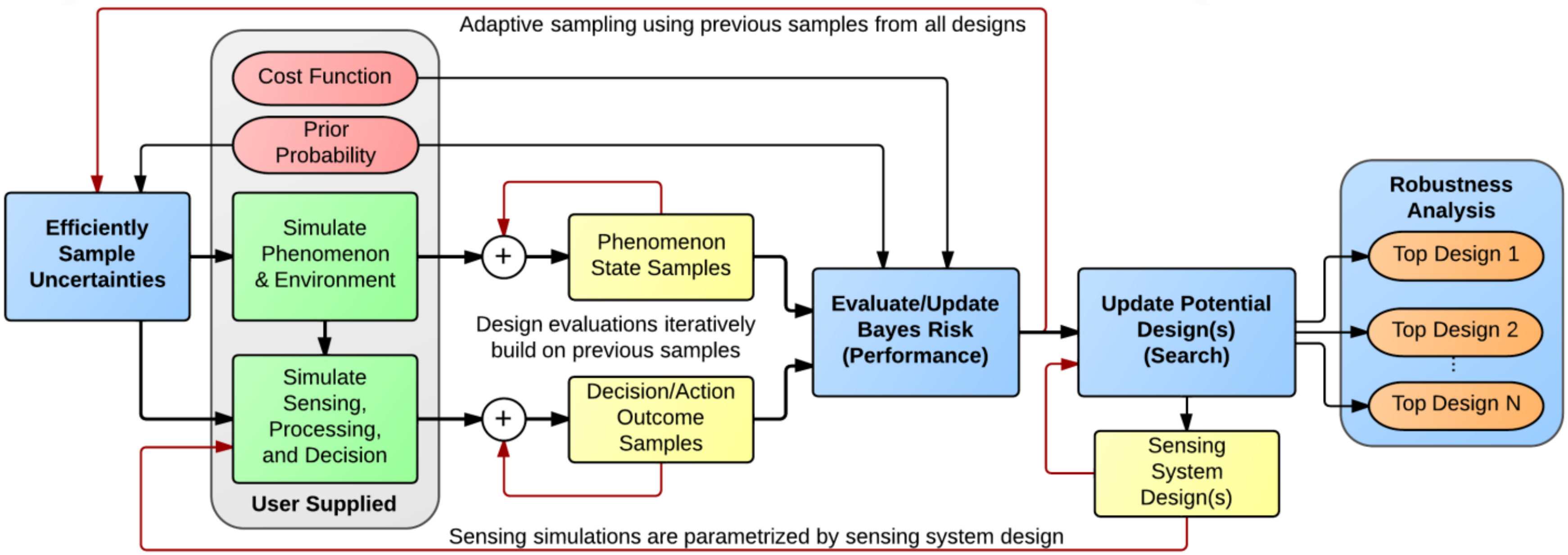
Crossover and mutate the survivors to repopulate

Generate new random sample and subject

Evaluate performance based on all previous samples

Respect your elders: The best design is the oldest design, not necessarily the best performer.

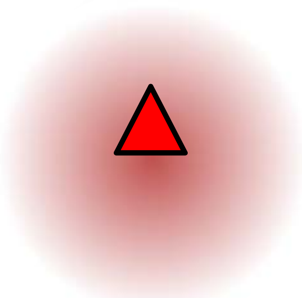
Plug-and-play Optimization



Surveillance Problem

Chemical, Biological, Radiological, Visual

Source

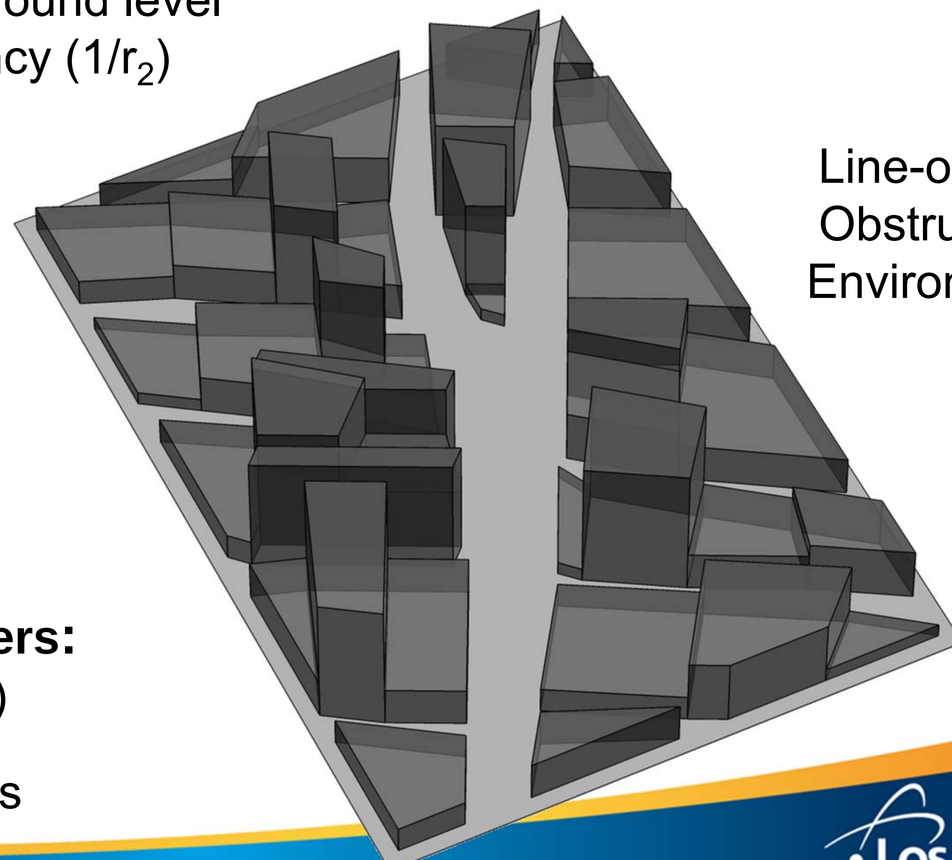


Known:
Occurs only at ground level
Radial dependency ($1/r_2$)

Unknown:
Location
Initial Intensity

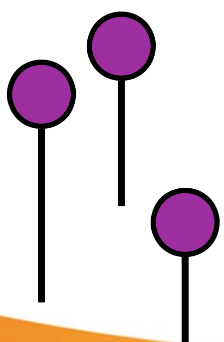
<u>Cost Function</u> Event Occurs: $1.0 B
Evacuation: $10.0 K

<u>Prior Probability</u> 1.0% over 10 years



Line-of-Site Obstructing Environment

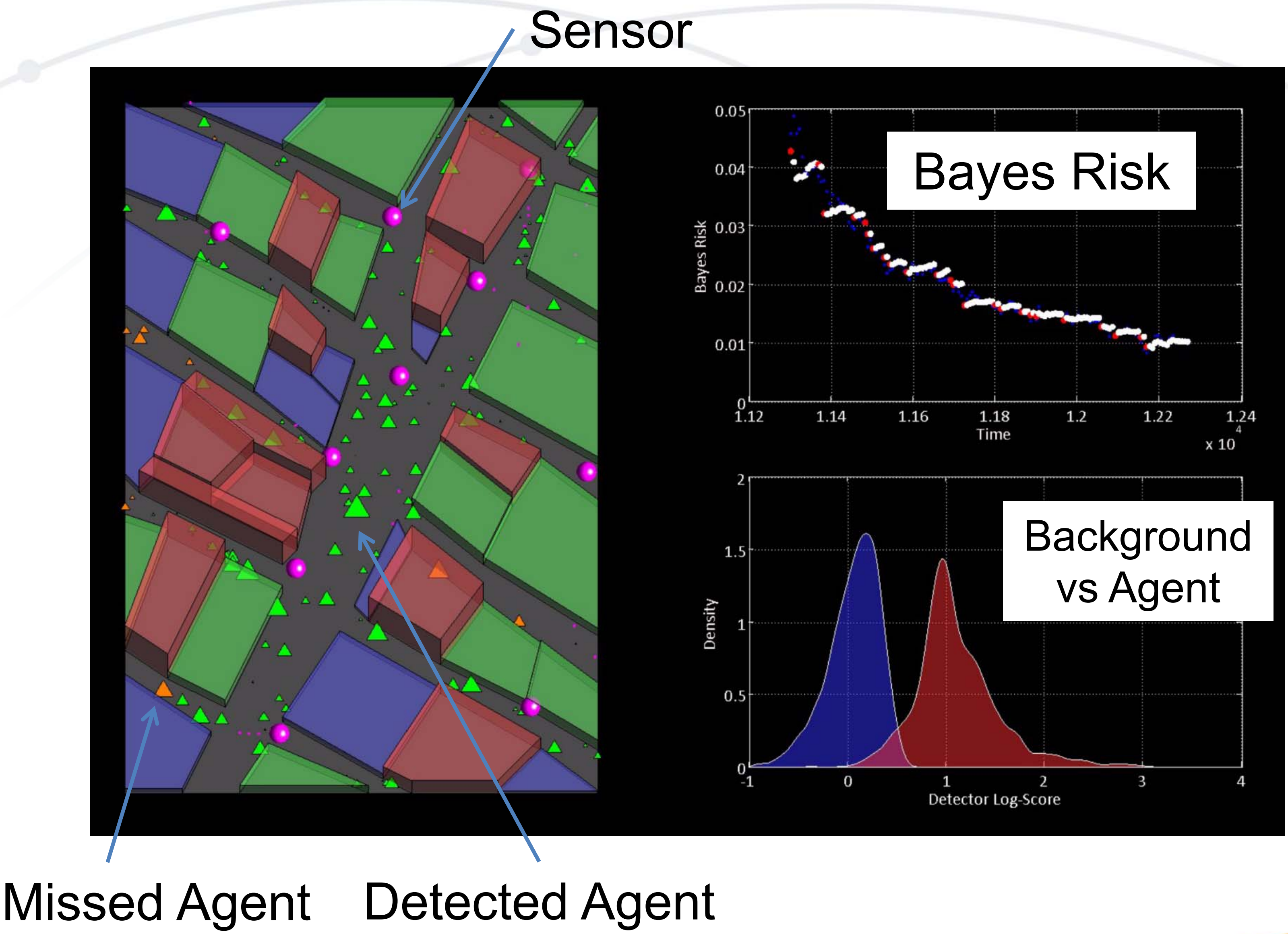
Sensor Placement



Measurement:
Intensity

Design Parameters:
Position (X, Y, Z)

Fixed: 10 Sensors


Sensor
Bayes Risk
0.05
0.04
0.03
0.02
0.01
0
1.12
1.14
1.16
1.18
1.2
1.22
1.24
Time
x 10^4
Background vs Agent
Density
2
1.5
1
0.5
0
-1
0
1
2
3
4
Detector Log-Score
Missed Agent
Detected Agent